The Unconventional Gas Program at the Lawrence Livermore National Laboratory

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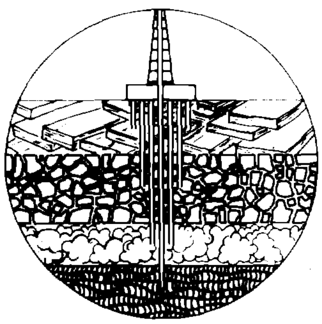
Prepared for the
LLNL Director's Review of Energy Programs
and for
Morgantown Energy Technology Center
Morgantown, WV

January, 1986

Lawrence Livermore National Laboratory



Unconventional Gas Program

Western Gas Sands Research

Eastern Devonian Shales Research

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

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1. INTRODUCTION

The Unconventional Gas Program at Lawrence Livermore National Laboratory is composed of two parts:

- the Western Gas Sands subprogram
- the Eastern Devonian Shales subprogram

1.1 Western Gas Sands Overview

The objective of the LLNL Western Gas Sands (WGS) subprogram is to improve the understanding of the stimulation mechanics of lenticular and jointed tight gas reservoirs. Particular emphasis is put on the interaction of induced fractures with natural fractures, and on the determination of relevant rock mass properties for input to hydrofracture simulators.

Accordingly, three tasks were pursued in WGS research in FY 1985:

- development of the FEFFLAP (Finite Element Fracture and Flow Analysis Program) computer model for arbitrary fluid-driven fracture propagation in discontinuous rock masses. FEFFLAP is a planar model. (R. Shaffer and F. Heuze).

- development of the PDCRAC (Pressure Driven Crack) three dimensional hydrofrac simulator. PDCRAC assumes independent elliptical geometries for the crack front and the fluid front and solves the double free-boundary problem in time and space. (R. Stout).

- mechanical properties estimates for sandstones and shales from 5 wells in the Mesaverde formation were obtained by 3 different methods and compared (W. Lin). A new procedure was proposed to back-calculate in-situ moduli of reservoir rocks from pressure-time stimulation records. (A. Wijesinghe).

1.2 Eastern Devonian Shales Overview

The objective of the LLNL Eastern Devonian Shales (EDS) subprogram is to provide better models and better diagnostics for the stimulation of tight shale reservoirs, with an emphasis on dynamic or tailored-pulse loading (TPL), and on geological reservoir characteristics such as rock properties, in-situ stresses and location of natural fractures.

Accordingly, there were five tasks under EDS research in FY 1985:

- continued development of a seismic reflection approach for locating natural fractures which do not intersect a well (J. Hearst).
- continued development of a tool to estimate in-situ stresses around gas wells, by measuring shear-wave velocity anisotropy induced by rock stresses (N. Mao).
- application of a geostatistical (kriging) method to analyze geological and gas production data from West Virginia shales (N. Mao).
- development of a dynamic numerical model to represent the interaction of gas-driven fractures with natural fractures, in shale reservoirs (R. Swift, R. Nilson, R. Shaffer).
- documentation of previously measured mechanical and sonic properties of West Virginia shales, up to the very high pressures (GPa's) encountered in dynamic/propellant stimulation (H. Heard, W. Lin).

Details of the results and accomplishments are given in the following two chapters. The final chapter outlines recommendations for future research which is considered essential to promote better understanding of the stimulation of tight gas reservoirs.

2. WESTERN GAS SANDS RESEARCH

2.1 Fluid-Driven Fracture Propagation in Jointed Rock

Version 1.0 of the FEFFLAP code was completed and documented. Both a theory manual [1] and a user's and verification manual [2] were prepared. This code is a fully coupled two-dimensional fracture and flow model capable of describing the interaction of fluid-driven fractures with interfaces such as joints, faults, contacts, etc., in rock masses made up of different rock types. The nonlinear mechanics of these geologic interfaces are accounted for.

Arbitrary stresses can be accommodated, as well as gravity. Both flow rate and flow pressure boundary conditions are possible. Induced fractures can propagate arbitrarily; they are not constrained to be in a predetermined direction. Thus the model can describe fracture curvature and fracture diffraction in non-homogeneous reservoirs. FEFFLAP is a highly graphics interactive finite element program. Fracture extension in the mesh is handled through automatic rezoning and automatic node renumbering, for minimizing bandwidth and computing time. The logic of the code is shown in Fig. 1.

An initial application of FEFFLAP [3,4] showed the steady-state fluid flow resulting from hydrofracturing in a reservoir with two sets of joints. The flow from the injection well spread out over a wide area, although most of it was concentrated in a single fissure. This computation helped to illustrate why at the Multiwell 1 site the seismic noises during a stimulation came from a band averaging 50 ft in width [5]. In such a jointed medium, the injection of fluid into joints adjacent to the main fracture will tend to make these joints slip, and will create microseismic activity.

Another example of FEFFLAP calculations is shown in Fig. 2, where a crack originating parallel to a lens is shown to extend in different manners depending upon the in-situ stress ratio and the modulus contrast between the lens (E_2) and the surrounding material (E_1). Points A and B correspond to $E_2/E_1 = 2$ when respectively $\sigma_x = 2.25\ \sigma_y$ and $\sigma_x = \sigma_y$. Points C and D correspond to $E_2/E_1 = 0.5$, with respectively $\sigma_x = \sigma_y$ and $\sigma_x = 2.25\ \sigma_y$.

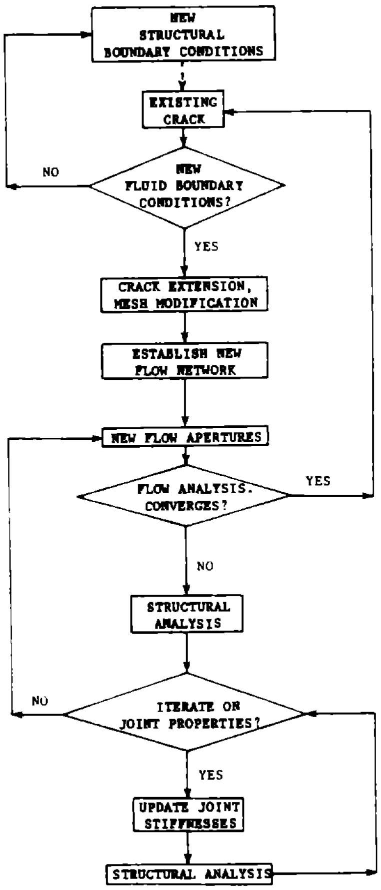

Figure 1: Logic of the FEFFLAP Code.

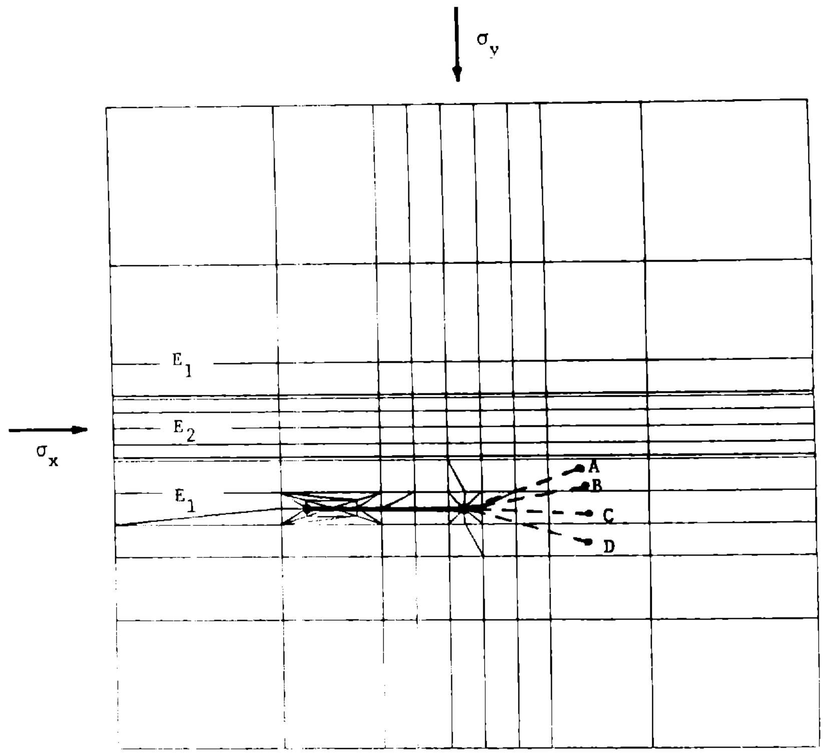

Figure 2. FEFFLAP Modeling of Hydrofracture Propagation Near a Lens.

Yet another recent application of FEFFLAP was to model observations made during hydrofracturing of the Blue Creek Coal Seam, Oak Grove Mine, Alabama. It was determined that the hydrofracture would not have moved out of the coal seam, into the shale roof, if the shale were intact; it was also calculated that an initial flaw as short as 1/4 inch in the shale would allow the hydrofracture to reinitiate and propagate in the roof, as observed in the field.

2.2 Three-Dimensional Hydrofrac Simulator

Version 1.0 of the PDCRAC code was completed and documented. The theory of the model was published previously [6]. The user's manual was produced in FY 1985 [7]. The crack front and the wetted front in the crack are modelled as two different free boundary problems. The shape of each front is an ellipse that propagates in the plane of the hydrofracture (Fig. 3). Typical profiles for fluid pressures and fluid velocities are shown on Figs. 4 and 5 respectively.

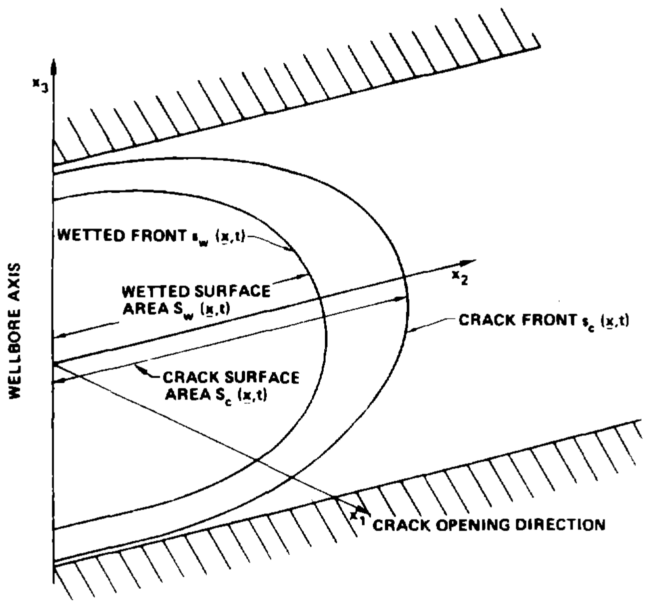

Figure 3: Crack and Wetted-Surface Geometries in PDCRAC

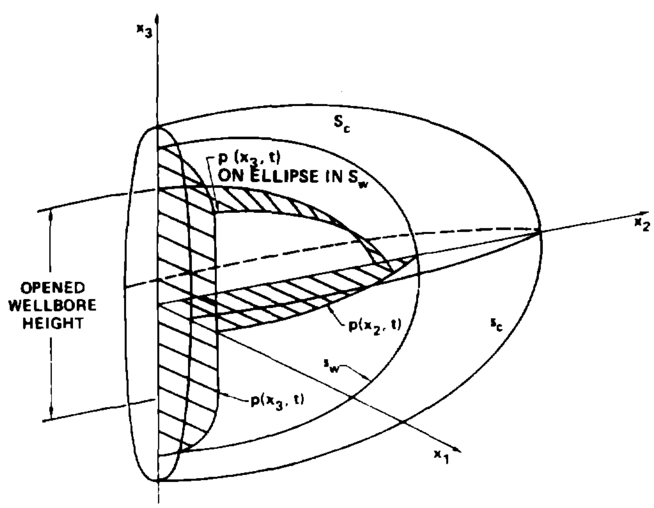

Figure 4: PDCRAC Fluid Pressure Profiles

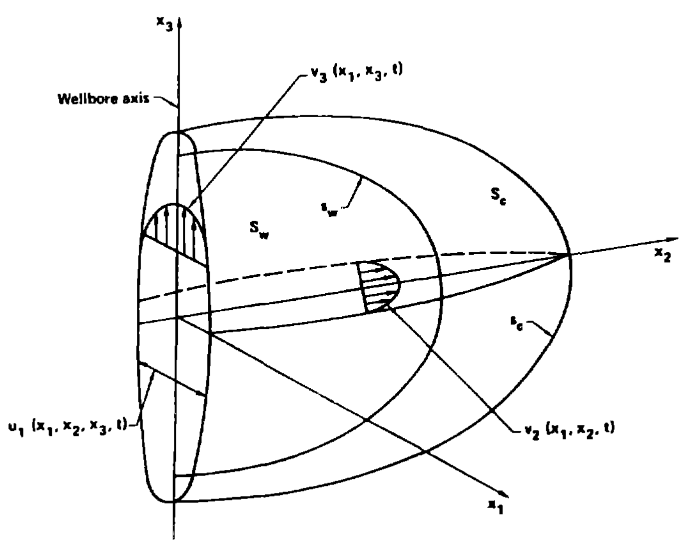

Figure 5: PDCRAC Fluid Velocity Profiles

The input requires initial conditions, geometry, elastic properties, fracture condition set by a threshold crack opening displacement, viscous fluid properties, and a wellbore pressure history adjacent to the crack (the code does not accommodate a flow rate history). The output consists of time histories for the crack opening, crack propagation velocities and fluid front propagation velocities along the two axes of the elliptical shaped crack and wetted fronts, (Fig. 5), lengths of the axes for elliptical shaped crack and wetted surface, and fluid flow rate. The influence of layers on crack propagation is simulated by the input of different fracture conditions for each layer. Generic calculations predict that significant separation can occur between the crack front and the wetted front during hydrofracture, because the crack propagation velocity is usually greater than the fluid front propagation velocity. Some exceptions to this separation are predicted for layered resource zones when crack arrest occurs.

A PDCRAC calculation was run to simulate the Paludal zone Phase I stimulation at Multiwell 1 (Minifrac No. 2), based on the results of Sandia [8]. The comparison between PDCRAC and field results are shown on Table 1. For additional comparison, the table also shows the results obtained with the SYMFRAC pseudo-3D simulator of Palmer [9,10].

Table 1. Comparison of Model Calculations with Results of the MWX-1 Paludal Zone Phase 1 Stimulation (Minifrac 2).

	Reported [8]	PDCRAC Model LLNL	SYMFRAC Model [9,10]
Pump time	~80 min.	74 min.	73 min.
Half-length	~400 ft.	455 ft.	440 ft.
Penetration above 7070 ft.	~50 ft.	20 ft.	41.7 ft.
Maximum Bottom Hole pressure above in-situ stress	~1200 psi	573 psi	388 psi
Maximum crack opening		.110 inch.	.085 inch.

In order to achieve a fracture length comparable to that reported in the field, both models had to use a smaller bottom hole pressure than the one actually measured. A possible explanation for this discrepancy is the pressure loss encountered in the field due to the roughness of natural fractures, to step cracks, and to fluid loss in multiple strands [11]. An additional possible factor in this difference is the choice of a higher modulus for the calculations than was the case in-situ. Such unanswered questions highlight the need to pursue two tasks under the LLNL Western Gas Sands research: models of fracture propagation in already fractured media, and definition of relevant rock mechanical properties for hydrofrac simulators.

Another calculation was made of the Sandia PTE-3 hydrofracture at G-Tunnel, Nevada Test Site [12]. The comparison of the PDCRAC and field results is shown on Figs. 6 and 7 for crack tip, and fluid front locations respectively. For this calculation the rock modulus was taken as $7 \cdot 10^5$ psi and the fluid viscosity as $1.01 \cdot 10^{-5}$ $\text{lbf} \cdot \text{sec/in}^2$.

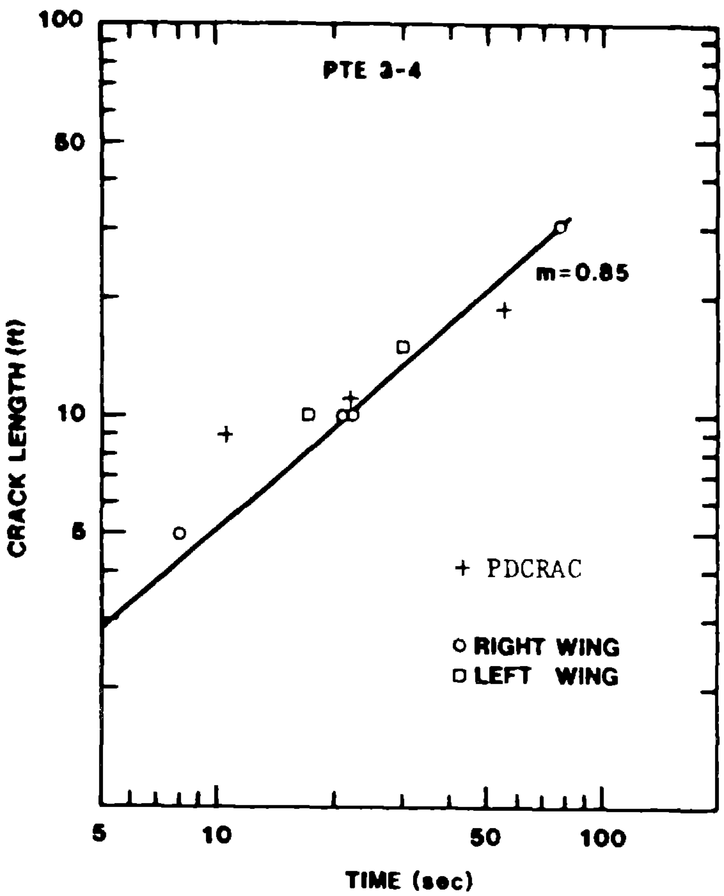

Figure 6: Comparison of Crack Tip Locations for PTE-3 Field Test, and PDCRAC Calculation.

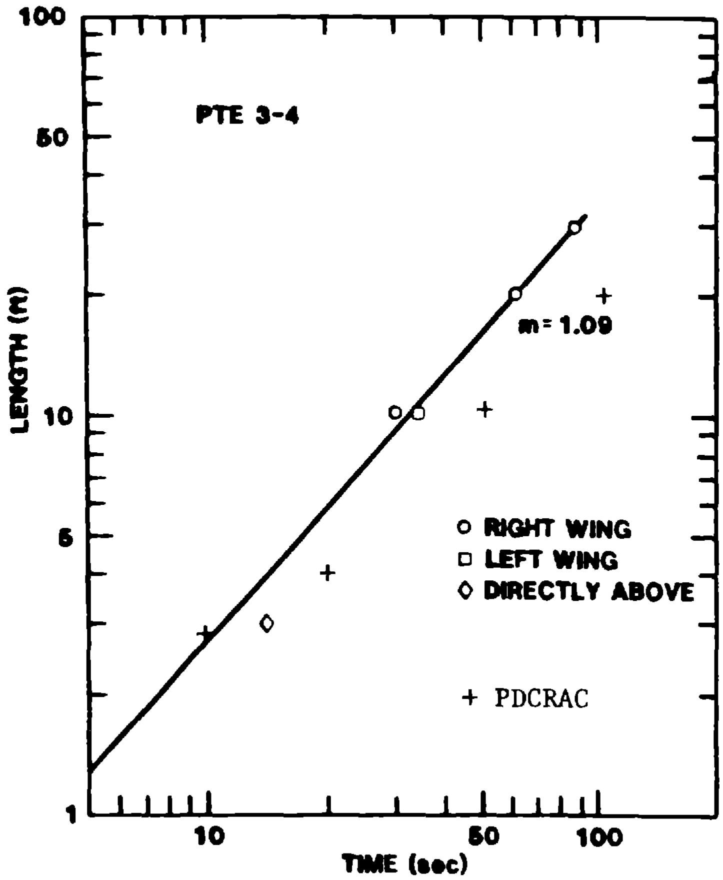

Figure 7: Comparison of Fluid Front Locations for PTE-3 Field Test, and PDCRAC Calculation.

2.3 Mechanical Properties of Mesaverde Rocks

A comparison of mechanical properties of Mesaverde rocks obtained by three different methods was achieved. Large discrepancies were found between the results. These results are consistent with similar discrepancies found by others, for rocks from the Multiwell site [13].

Shales and sandstones from wells Twin Arrow C and K 4-14 (CO), PTS 24-19 Federal (WY), PTS 22-12 Federal (CO), PTS 3-10-A (WY), and Rainbow Resources 1-3 Federal (WY) were characterized as follows:

- static laboratory tests for stiffness and strength [14].

- sonic (dynamic) laboratory tests, from which elastic moduli were calculated [15].

. well sonic logs from which in-situ elastic moduli were calculated and compared to the moduli obtained with the other two methods [16].

Only illustrative examples of the complete study are excerpted here. The first one, shown in Table 2, is a two way comparison between selected laboratory dynamic and laboratory static moduli and Poisson's ratios; E_x is the modulus in the bedding plane, E_z is the modulus perpendicular to bedding and ν_{xy} is the in-plane Poisson's ratio. G_{xy} is the in-plane shear modulus which is not independent; it is calculated as $E_x/2(1+\nu_{xy})$.

Results were obtained at a mean pressure (P_o) corresponding to that at the depth from which the samples came. The difference in moduli range from 60% to over 600%, and the dynamic Poisson's ratios appear very inconsistent.

Table 2: Comparison of Static Laboratory (S) and Dynamic Laboratory (D) Moduli for Mesaverde Rocks. (Moduli are in GPa)

Well	Rock type	E_x^D/E_x^S	E_z^D/E_z^S	ν_{xy}^D/ν_{xy}^S	G_{xy}^D/G_{xy}^S
PTS 24-19	Sandstone	$\frac{47.62}{10.45}$	$\frac{42.55}{10.3}$	$\frac{0.017}{0.37}$	$\frac{23.41}{3.8}$
	Shale	$\frac{51.02}{8.14}$	$\frac{42.02}{7.16}$	$\frac{0.21}{0.31}$	$\frac{21.08}{3.11}$
PTS 22-12	Sandstone	$\frac{66.67}{41.05}$	$\frac{65.36}{42.27}$	$\frac{-0.011}{0.20}$	$\frac{33.72}{17.18}$
	Shale	$\frac{75.19}{17.86}$	$\frac{58.14}{21.14}$	$\frac{0.22}{0.35}$	$\frac{36.79}{6.64}$
1-3 Federal	Sandstone	$\frac{66.23}{23.36}$	$\frac{60.98}{21.82}$	$\frac{-0.11}{0.27}$	$\frac{37.02}{9.23}$
	Shale	$\frac{56.50}{10.34}$	$\frac{47.17}{8.86}$	$\frac{0.11}{0.33}$	$\frac{25.57}{3.69}$

A three-way comparison is shown in Fig. 8 for two stiffness coefficients on rocks from PTS 24-19. These in turn are related to the moduli and Poisson's ratios [14]. Fig. 8 shows that calculated dynamic values from the field logs and the laboratory sonic test do not even necessarily agree, although the discrepancies are smaller than between static and dynamic tests. Because the rock mass deformation under hydrofracturing is a quasi-static process, the above results convincingly demonstrate that dynamic moduli calculated from field sonic logs are inappropriate for input into hydrofracture simulators. Because of well known scale effects [17], the static laboratory tests are not appropriate either. Thus, future research must concentrate on how to estimate in-situ the static stiffness of reservoir rocks. For uncased holes, a borehole deformation tool operated during hydrofracture has been proposed [18]; however, it would not be usable in hydrofracs with perforated casings. A preliminary study was performed at LLNL on a possible alternative; it is based on the back analysis of actual stimulation pressure time records, under restrictive assumptions of fracture growth. The procedure is described in reference [19].

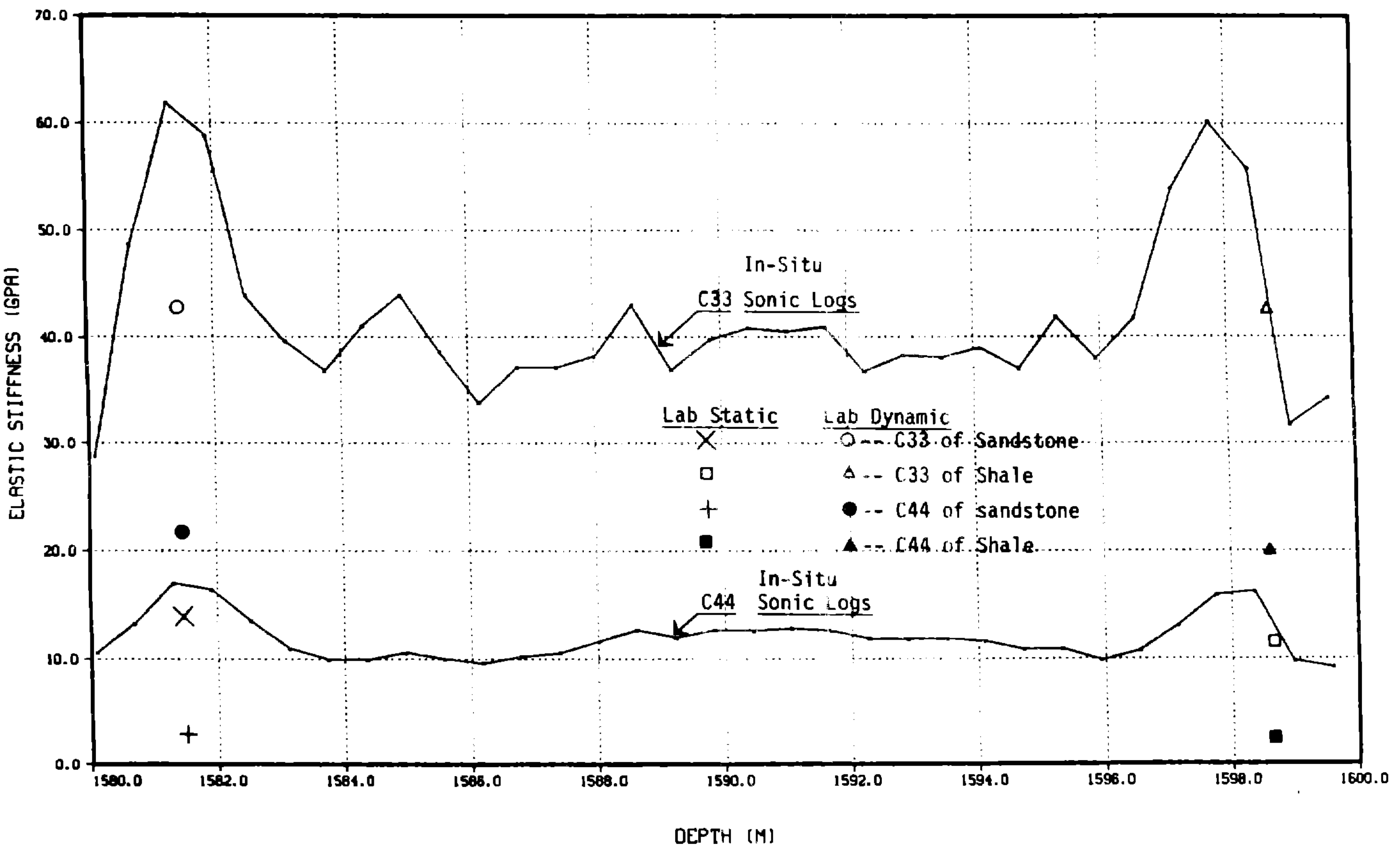

Figure 8: Comparison of Stiffness Coefficients C33 and C44 Obtained by Three Different Methods on Shales and Sandstones from Well PTS 24-19.

3. EASTERN DEVONIAN SHALE RESEARCH

3.1 Remote Fracture Sensing by Sonic Reflection

We have been attempting to use the reflection of sonic waves to sense fractures which do not intercept wells. A previous effort based on P-waves was not successful [20]. We concluded that the presence of a large direct wave made it impossible to see the reflected signal. This new effort was based on S-waves. There are some indications that high frequency S-waves hold promise to detect fractures away from boreholes; both laboratory [21] and field [22,23] results have been reported, although the field experiments are not fully conclusive yet.

In the FY 1985 effort [24], shear-wave transducers were built for us by Southwest Research Institute (Figure 9). They were designed to operate at 20 kHz, so that the wavelength, in hard rock, would be approximately the same as the transducer length. They were also designed to minimize the direct wave. The 10-cm-long jagged edge of the transducer contacts the rock. It was hoped that such an edge would be better than a solid edge at being able to make contact with a rough surface, and would act as an array, which should help in reducing the direct wave. The vibration of the transmitter is perpendicular to the long edge.

We tested the transducers on granite slabs, attempting to observe reflections from a free surface. The transmitter was excited by a single pulse, about 80 microseconds long. We used common-depth-point stacking to enhance reflected signals. The direct wave was considerably shorter than that seen with the transducers used in the past, and we observed events at the times at which reflections would be expected. The stacked record for the 62-cm thick slab is shown in Figure 10. The event at 0.472 ms is very close to the expected time for the reflection from the bottom, that at 0.943 ms is close to the double bounce time, and that at 0.562 ms is right for a reflection from the side.

The results from the optimal reflectors need to be confirmed with real in-situ conditions. Future proof of concept tests should take place at an actual rock site. This could be the granite quarry where the 1983 field tests were performed.

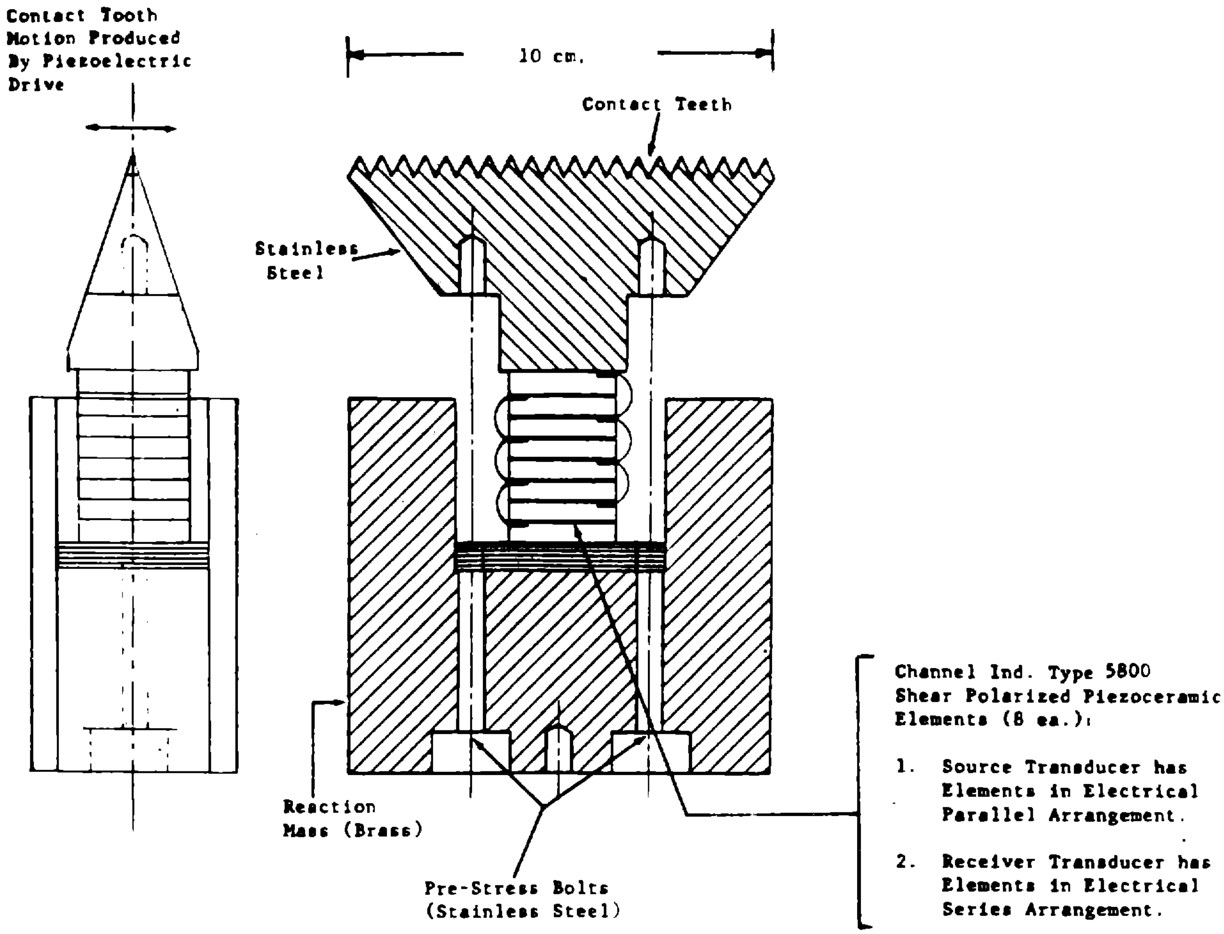

Figure 9: Shear Transducer Design and Assembly (Southwest Research Inst.).

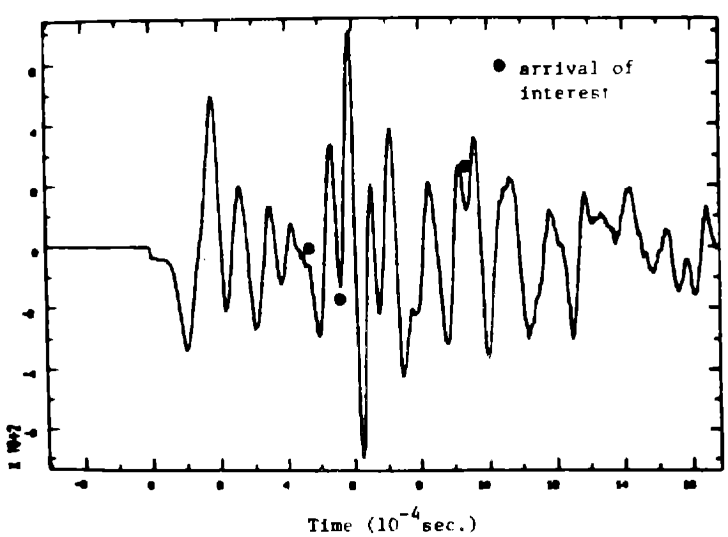

Figure 10: Stacked Signals from the 62-cm Block Tests.

3.2 Sonic In-Situ Stress Tool

A new prototype of the LLNL sonic stress tool was completed. Both the theory and the initial laboratory probe have been described previously [25,26]. The new instrument [27] embodies several significant advances towards a viable field prototype. The probe and its laboratory set up are shown on Figs. 11 and 12.

- the probe, which operates in 6-in. diameter holes, now has 12 cylindrical wedge transducers in four groups arranged at 90° to each other; each transducer group has one transmitter and two receivers. From the travel time difference and the separation of the two receivers, absolute travel times and velocity differences can now be calculated, as opposed to travel time differences previously measured. This provides much better stress estimates because fewer assumptions are involved. Figure 13 shows sample waveforms from both near and far receiver pairs. The calculated velocities are 2.350 and 2.326 km/s for tangentially and radially polarized shear waves respectively.

- the orientation of secondary principal stresses perpendicular to the hole can be estimated from the measured velocity anisotropy around a hole. Figure 14 shows a plot of relative travel time of tangentially polarized shear waves as a function of transducer orientation. A vertical stress of 1000 psi and a horizontal stress of 2500 psi were applied. As expected, the velocity at 90° (hole bottom) is the fastest of all, because of the stress concentration. If we did not know the stress orientation, we would choose as principal stress directions those of the velocity extremums.

- the polyurethane cell in which the transducers are embedded is expandable; the maximum bladder inflation pressure is 10,000 psi. By applying different stresses to the hole, in addition to the existing in-situ stress, one can calibrate the stress-velocity relationship for the rock in place.

- we also developed new data acquisition software for the Tektronix 7D20 Digitizer and the Hewlett Packard 3497A Data Acquisition Control Unit. More accurate calculations of the reference starting time enhance the travel time estimation.

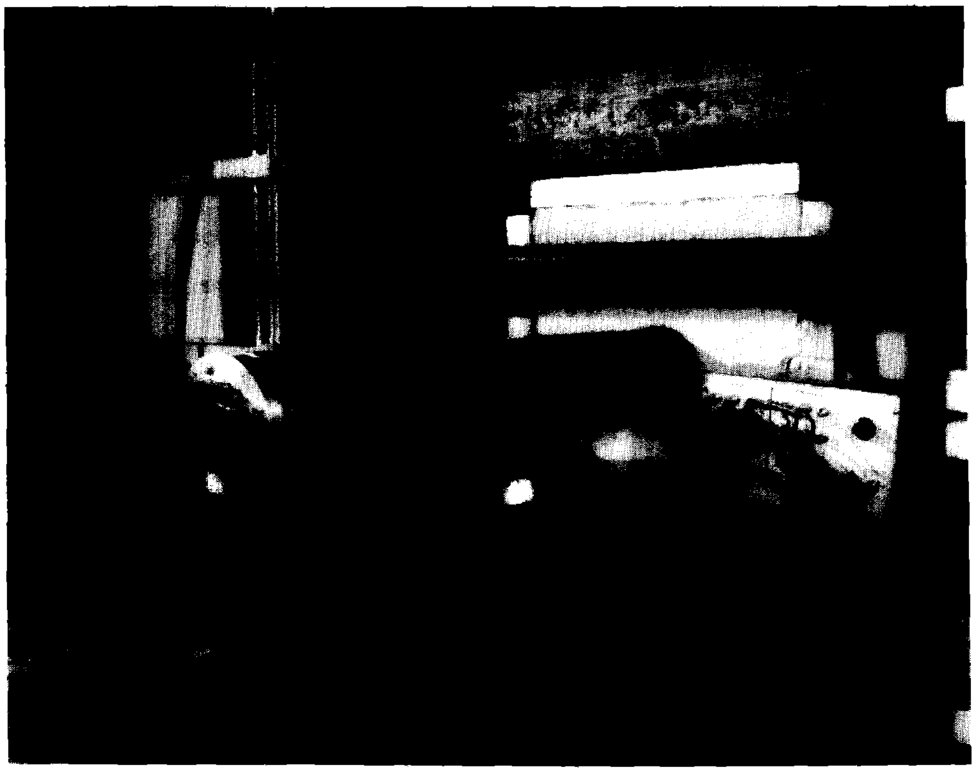

Figure 11: Close-Up of the New Sonic Stress Tool.

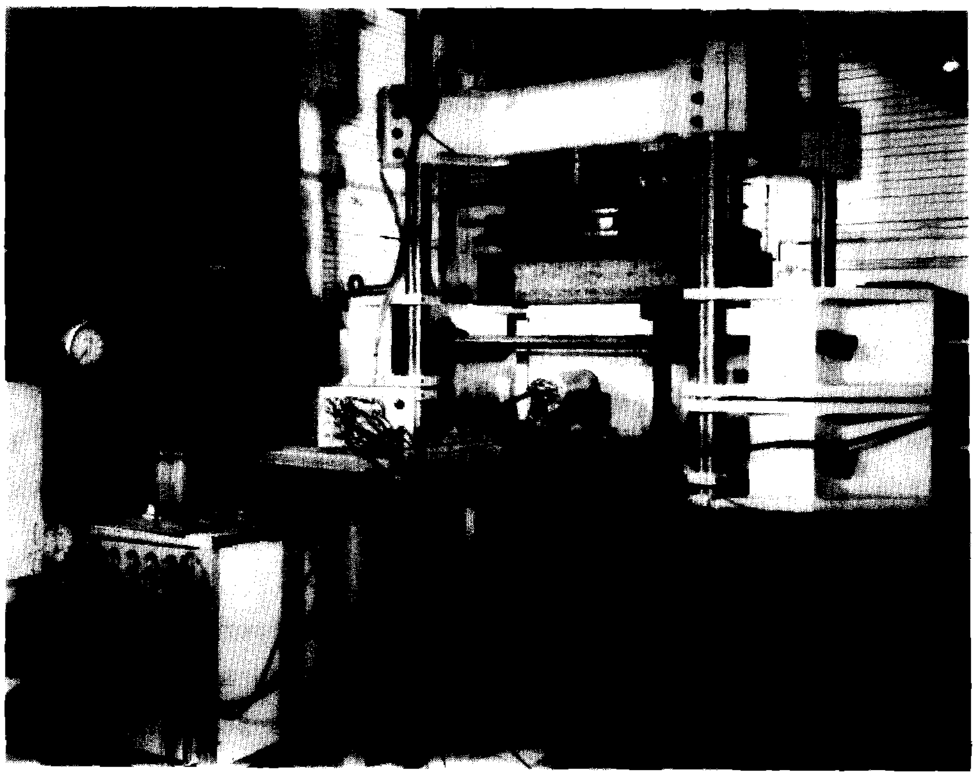

Figure 12: Laboratory Set-Up for Testing of the Stress Tool.

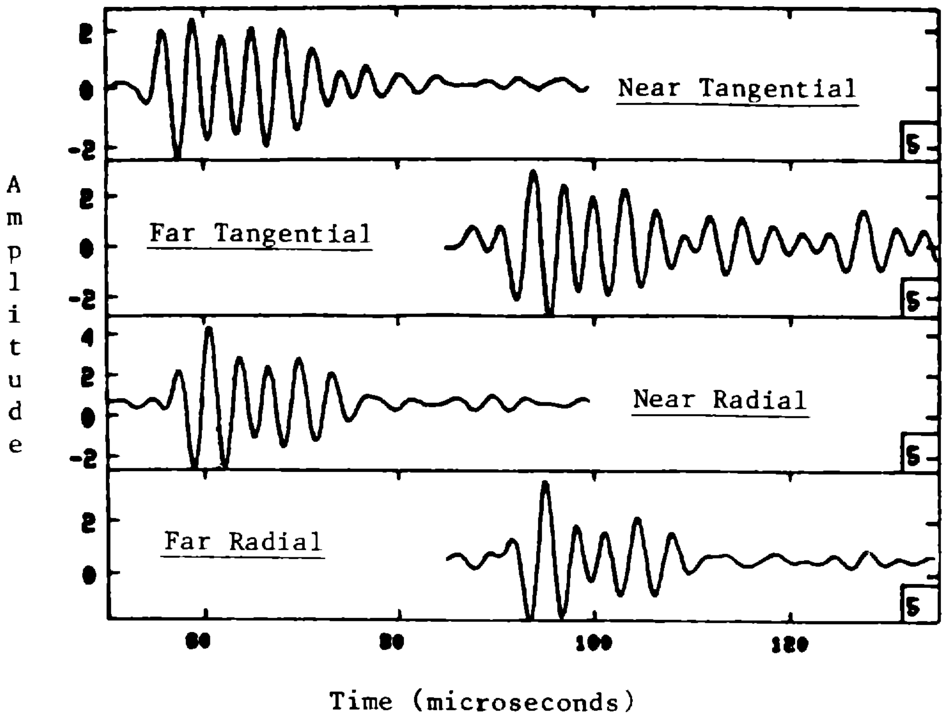

Figure 13 : Sample Wave Forms from Near and Far Receiver Pairs.

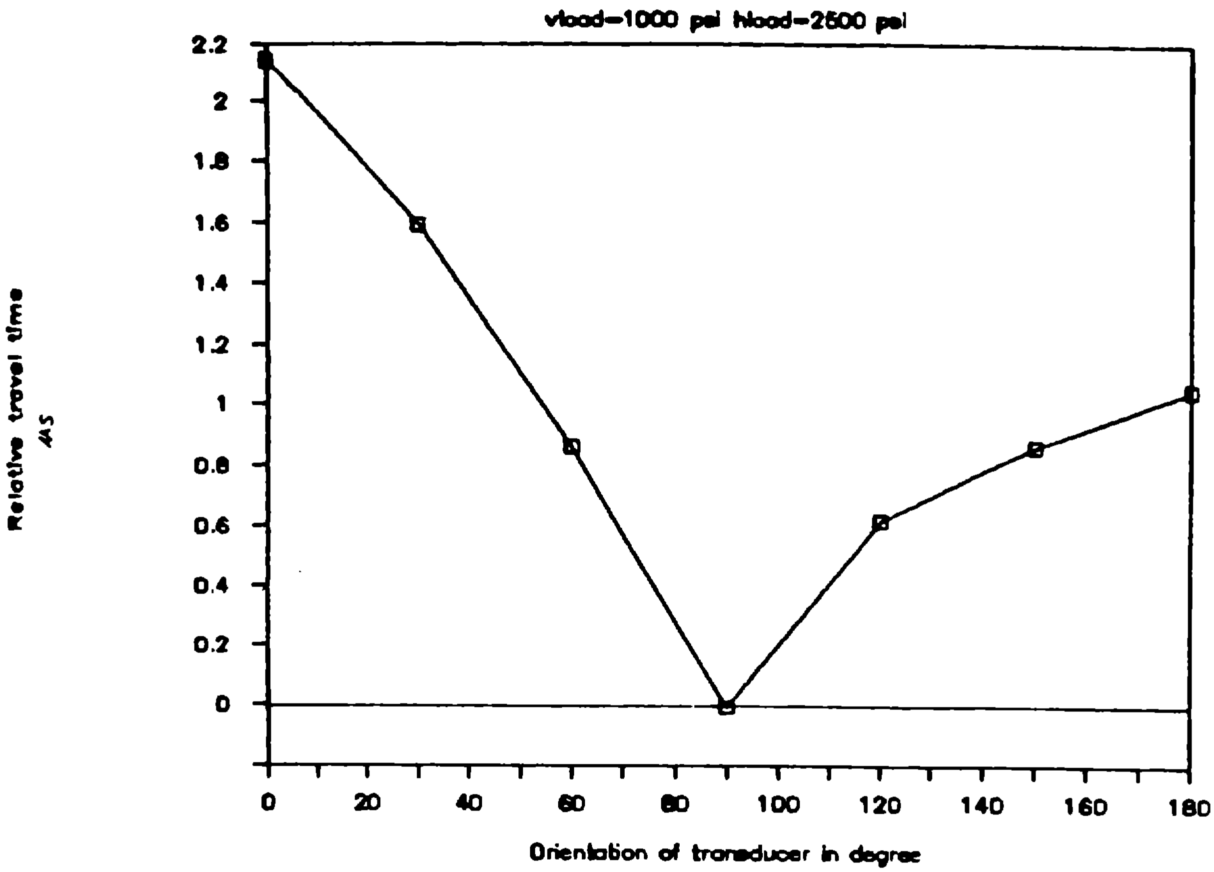

Figure 14 : Typical Relative Travel Time of SH-Wave, vs. Orientation.

3.3. Geostatistical (Kriging) Analyses of EDS Database

This task was initiated and completed in FY 1985. The kriging technique developed at the French National School of Mines [28] has been used for some time at LLNL, to study the geology of the Nevada Test Site, in support of the nuclear test program [29]. It was then applied to the geology and production data from a West Virginia field. The results are documented in a topical report [30]. The database was supplied by METC from the Columbia Gas System Service Corporation's eastern gas shale database with corrections to well locations by EG&G Washington Analytical Services Center, Inc. There are 617 wells in the study area including part of Lincoln, Logan, Mingo, and Wayne counties. Because of space limitation only the 10-year cumulative production data (10 CUP) are discussed here. Because 10 CUP have a lognormal distribution it is the logarithm of 10 CUP which is used as a variable.

Figure 15 shows the variogram (variance vs. distance) of log (10 CUP). The finite variance at zero distance (the so-called nugget effect) implies that large variations can occur over short distances; this can be due to the scarcity of data over short distances, or to the own uncertainty of the data. However, the correlation is well pronounced for distances between about 10 and 70 units; one unit is 10^{-3} degree.

Figure 16 shows the kriged contours of log (10 CUP). The subsurface geologic data, which correlated well with the surface data, reflected the presence of the Guthrie syncline (S) and of the Warfield anticline (A). These features have been superimposed on Fig. 16. The figure shows a trend of lower cumulative production along the direction of the anticline axis. If this observation can be extended to neighboring fields, it could provide some guidelines for future exploration.

3.4. Model of Tailored Pulse (TPL) Gas Well Stimulation

This task relates to the need for better understanding of the dynamic stimulation of gas wells. After performing a detailed critical review of the state of the art in TPL modeling [12], it became clear that the problem of explosive gas-driven fracture modeling had only been approached in parts, and that there was essentially no tool for the analysis of propagation of such multiple fractures in naturally jointed media.

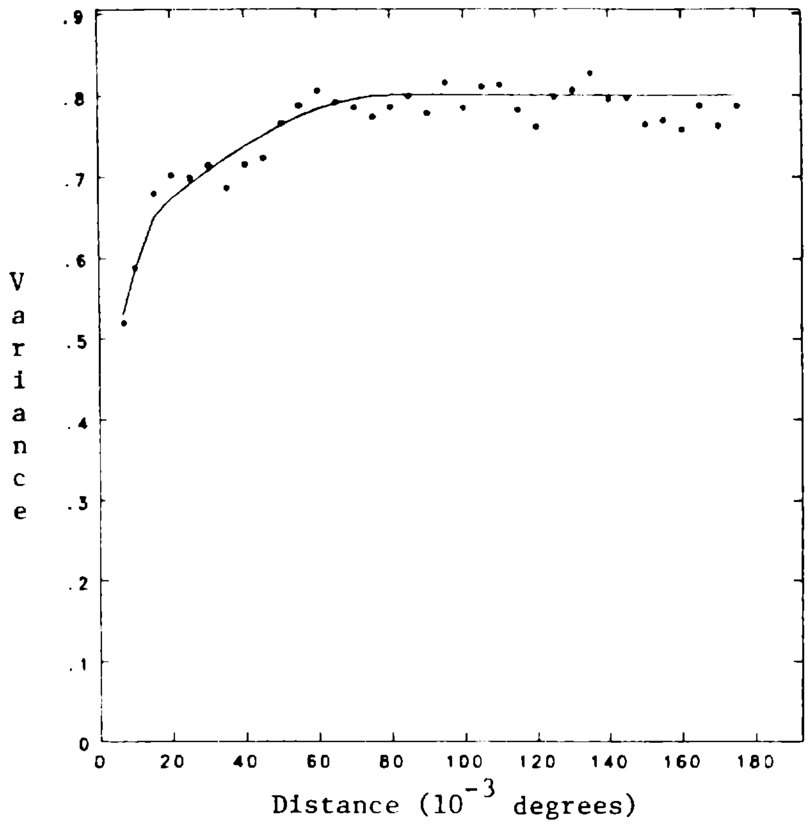

Figure 15: **Variogram of Log (10 CUP), Columbia Gas, EDS Database.**

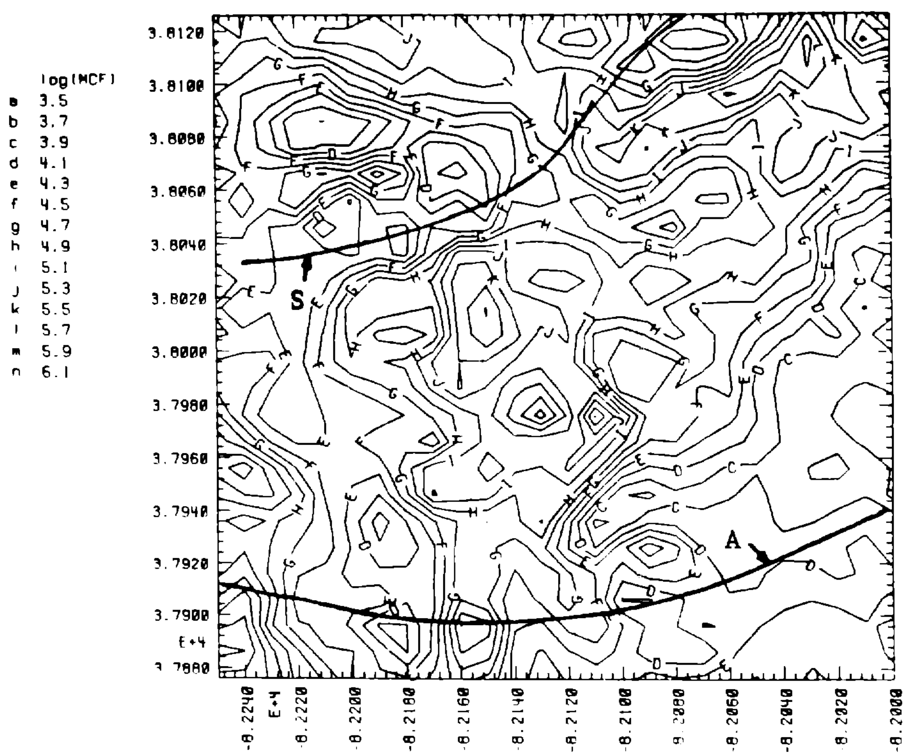

Figure 16: **Kriged Contour Map of Log (10 CUP).**

We then evolved a strategy to develop an initial TPL modeling capability for real geologic media; it consists of coupling the FAST gas dynamics and fracture analytical module of S-Cubed [32] to our FEFFLAP model for fluid-driven fractures in jointed rock [1,2] developed under Western Gas Sands Research. This task was initiated in FY 1985. Completion and topical reporting are expected in 1986.

3.5. High-Pressure Mechanical and Sonic Properties of Eastern Devonian Shales

This work was performed several years ago but never was formerly reported in a comprehensive fashion. This has now been remedied. Static mechanical properties and sonic velocities were determined on each of four members of the Devonian shale from Columbia Gas Transmission's well 20403, Huntington, West Virginia. They were:

- pressure - volume data to 4.0 GPa
- triaxial compressive strength at confining pressures up to 300 MPa, parallel and perpendicular to bedding.
- triaxial extensile strength at 100 to 700 MPa confining pressure, parallel and perpendicular to bedding.
- loading and unloading path in controlled strain at 20 to 500 MPa confining pressure, parallel and perpendicular to bedding.
- tensile strength at ambient pressure, parallel and perpendicular to bedding.
- shear and compressional wave velocities at confining pressures up to 1000 MPa parallel, at 45°, and perpendicular to bedding.

The unique features of several of these tests are the very high pressures. The results are directly relevant to the very high stress conditions encountered in TPL loading, and as such will be useful as input to TPL models. Only selected results are presented here; full details are given in [33]. Sonic wave velocities (Figure 17) and stiffness coefficients (Figure 18) showed strong variations with pressure. The tensile strength was essentially independent of depth as shown in Figure 19.

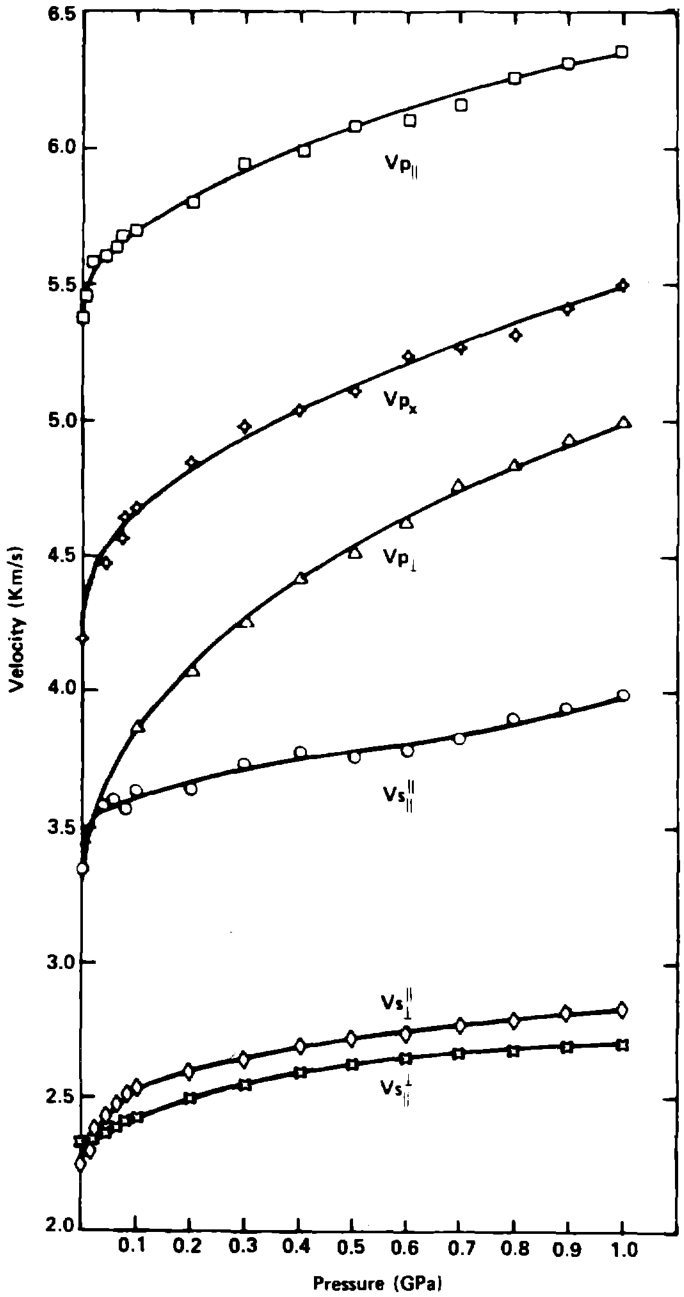

Figure 17: Sonic Velocities vs. Pressure, Olentangy Shale, Depth 1195 m.

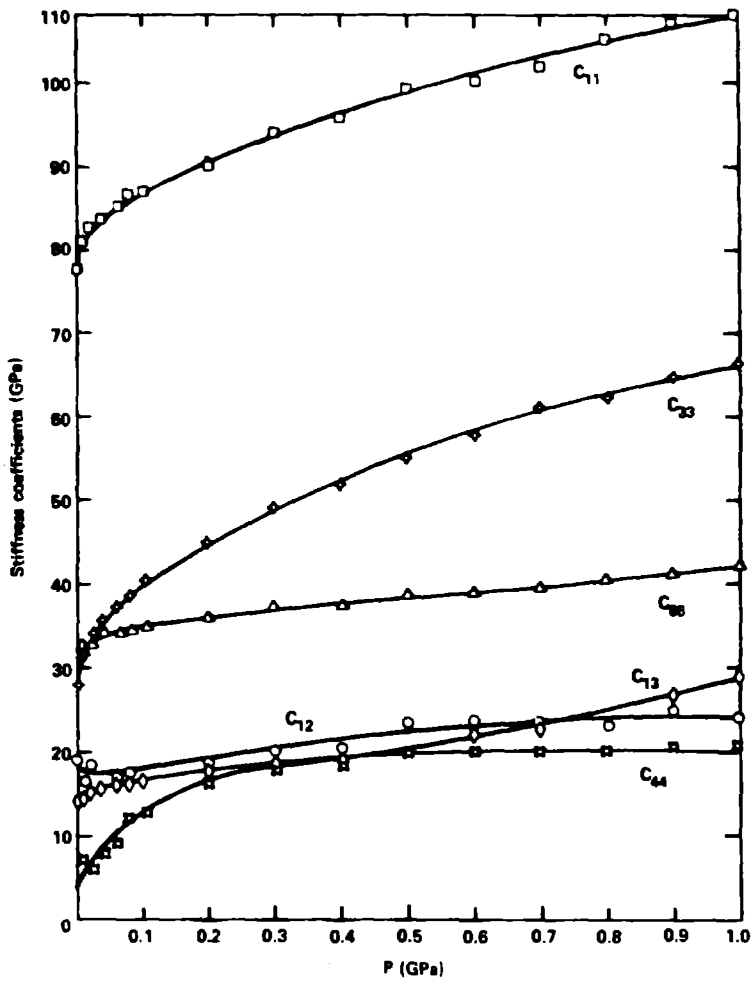

Figure 18 : **Stiffness Coefficients vs. Pressure, Olentangy Shale, Depth 1195 m.**

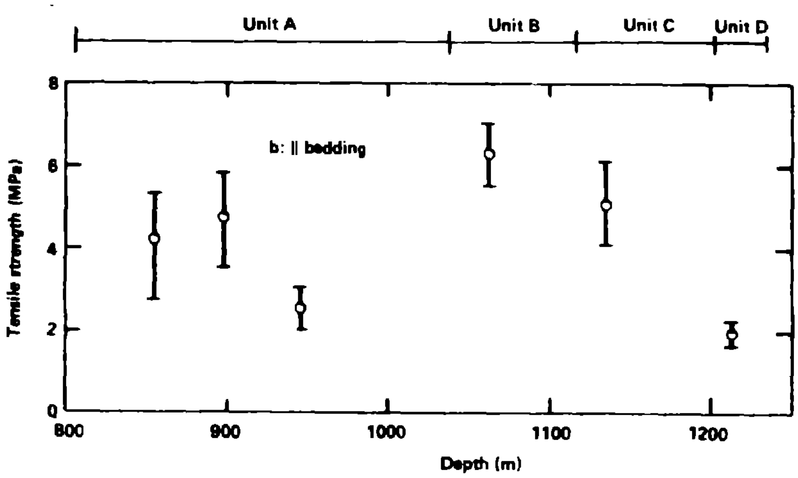

Figure 19 : **Brazilian Tensile Strengths for the Four Shale Units.**

4. SUMMARY - RECOMMENDATIONS

Our results strongly suggest that two types of activities should be part of future Western Gas Sands research.

- it is necessary to continue developing a better understanding of the interaction of induced fractures with natural fractures. This will have useful applications in the stimulation of lenses away from wells. It is expected that new models will permit the characterization of pressure-time records regarding lens-entry, lens-exit and lens-refraction of hydrofractures. These models should be verified on carefully planned physical experiments.

- additional effort must be put into getting relevant (in-situ) moduli of Western Gas reservoirs. This could be achieved by direct in-situ tests in open holes if such holes can be tested with jacks and dilatometers, as is the practice in the civil and mining field. In cased holes, the back analysis of stimulation records should be actively pursued, with the help of both constant height and variable height simulators.

As for Eastern Devonian Shale research:

- the present sonic stress system is adequate for laboratory tests. However, for field test, even at fully equipped field facility such as the Spent Fuel Test Climax (SFT/C), Nevada Test Site, additional modifications of the probe are required. One of the modifications is to have a dual pressure system so that the pressure behind transducers is separately controlled. Another modification is to have rotating block design for the end cap to allow for more expansion of the bladder. We are currently working on these modifications. We intend to test the improved instrument in the field, at a location such as SFT/C where in-situ stresses have already been estimated by other techniques, in order to allow for a comparison with the new method. Beyond that stage, it is recommended that a gas reservoir stress tool prototype be built and fielded.

- we believe that a small level of funding could reasonably be put into testing the new shear transducers for sonic reflection mapping in a quarry, as discussed in 3.1, so as to determine the viability of the new approach adopted in FY 1985.

- it appears important, as well, to continue the development of more realistic models of TPL stimulation in prefractured reservoirs, so as to enable more than empirical extrapolations of the existing field trials. Such research can profitably build upon the advances made in fracture modeling under Western Gas Sands funding.

5. REFERENCES

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6. ACKNOWLEDGMENTS

This report was prepared by the LLNL Unconventional Gas Program, under contract W-7405-ENG-48 with the U. S. Department of Energy. Gas Program monitoring is performed by Morgantown Energy Technology Center, Morgantown, WV.

The author, and Program Manager, is very grateful to his colleagues: H. Heard, J. Hearst, W. Lin, N. Mao, R. Nilson (S-Cubed), R. Shaffer, R. Stout, and R. Swift for their fine contributions.